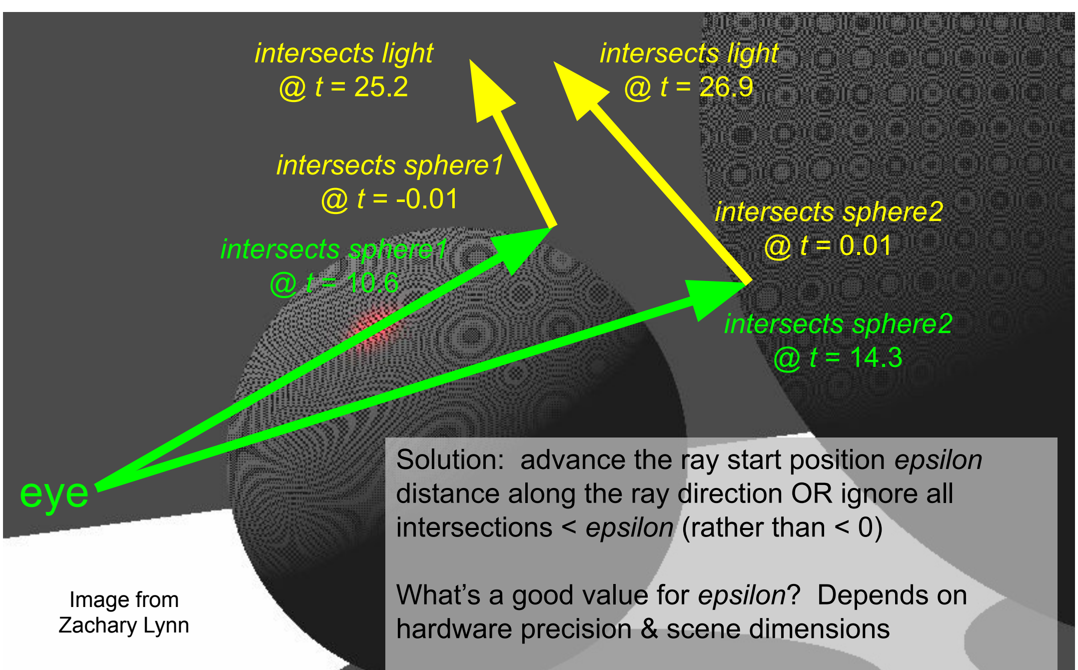
The Rendering Equation
& Irradiance Caching
& Photon Mapping

HW3: Raytracing & Epsilon



Solution: advance the ray start position *epsilon* distance along the ray direction OR ignore all intersections < *epsilon* (rather than < 0)

What's a good value for *epsilon*? Depends on hardware precision & scene dimensions

Image from Zachary Lynn

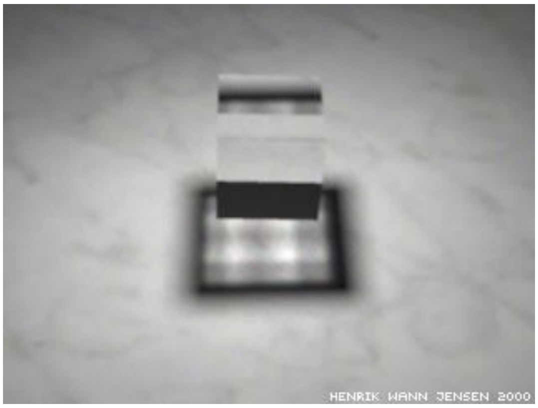
Final Project Brainstorming

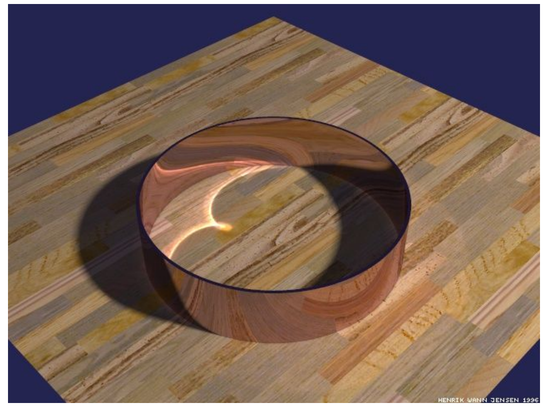
- Each student should post two different ideas for a final project on the forum.
  - For each idea:
    - Briefly describe the idea, your motivation for it, and an example of the potential result.
    - What is the significant/interesting technical implementation challenge?
  - Have you already decided on one idea? Which one?
  - Do you already have a partner? Who?
    (even if you have chosen an idea and/or a partner everyone must post 2 different ideas)
  - Due Wednesday 3/17 @ 11:59pm)
- Teams of 2 strongly recommended
  (individuals & teams >2 require instructor permission)
- *Projects from prior terms are on the website*

The Light of Mies van der Rohe

Henrik Wann Jensen, SIGGRAPH 2000

Is this Traditional Ray Tracing?



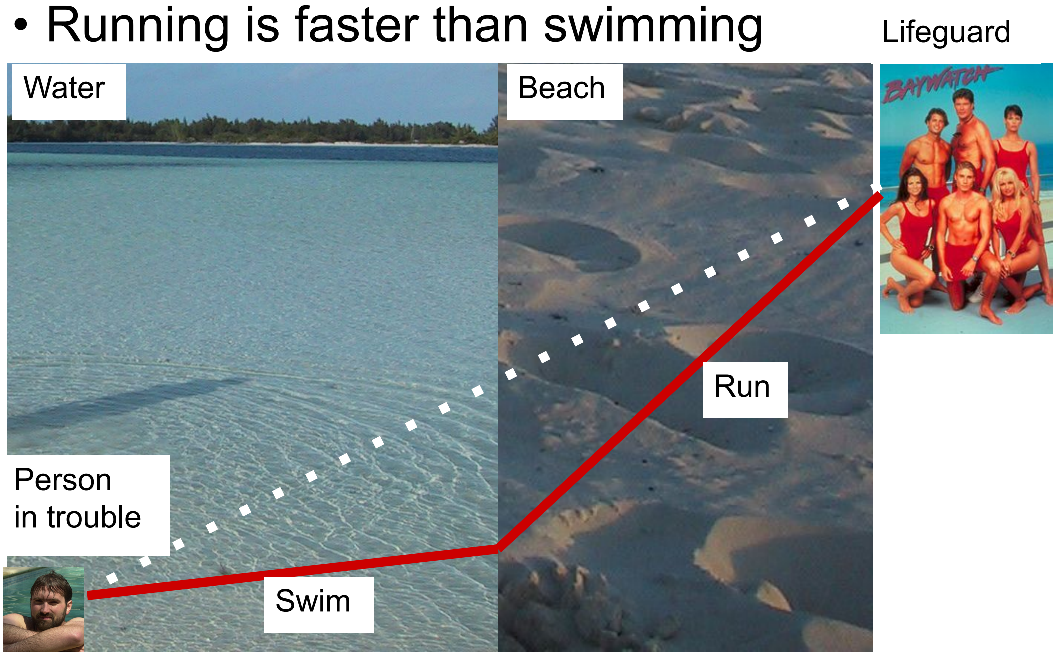


Images by Henrik Wann Jensen

No. Refraction and complex reflections for illumination are not handled properly in traditional (backward) ray tracing.

Refraction and the Lifeguard Problem

- Running is faster than swimming



Today

- The Rendering Equation
- Worksheet on Progressive Radiosity
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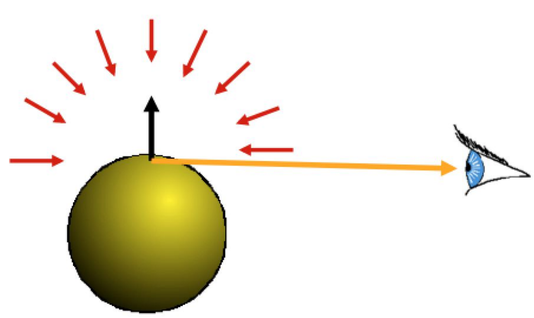
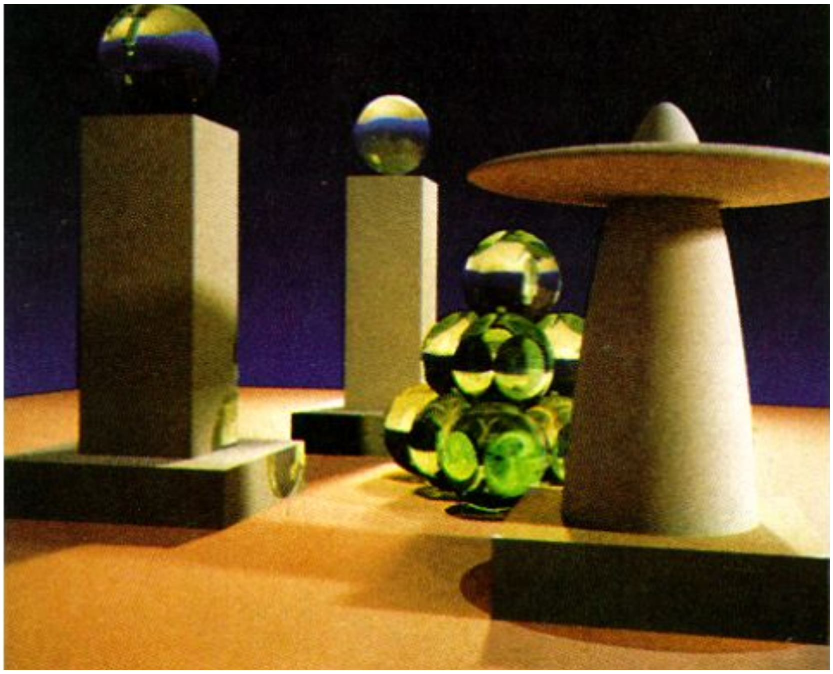
The Rendering Equation

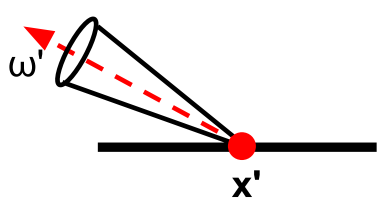
- Clean mathematical framework for light-transport simulation
- At each point, outgoing light in one direction is the integral of incoming light in all directions multiplied by reflectance property



“The Rendering Equation”, Kajiya, SIGGRAPH 1986



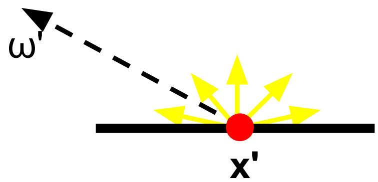
The Rendering Equation



$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\, dA$$

L (x',ω') is the radiance from a point on a surface in a given direction ω'

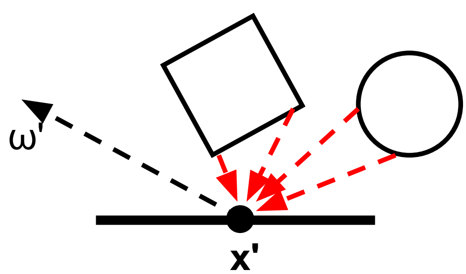
The Rendering Equation



$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\,dA$$

E(x',ω') is the emitted radiance from a point: E is non-zero only if x' is emissive (a light *source*)

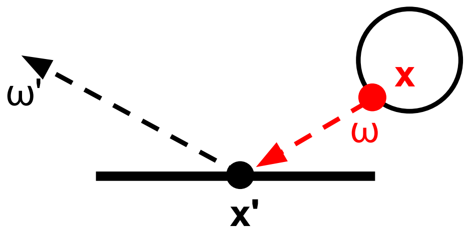
The Rendering Equation



$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\,dA$$

Sum the contribution from all of the other surfaces in the scene

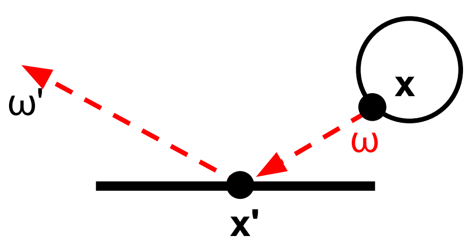
The Rendering Equation



$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\,dA$$

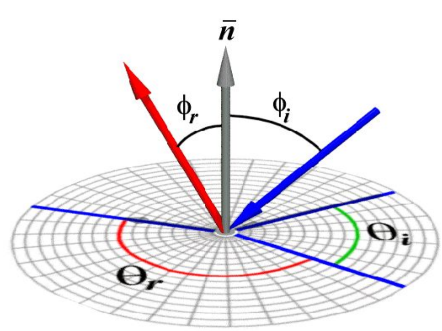
For each x, compute L(x, ω), the radiance at point x in the direction ω (from x to x')

The Rendering Equation

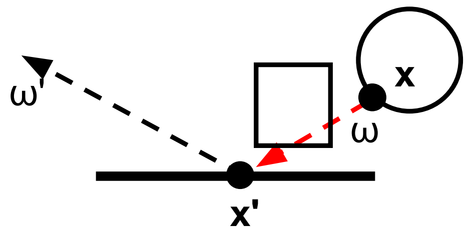


$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\,dA$$

scale the contribution by $\rho_{x'}(\omega,\omega')$, the reflectivity (BRDF) of the surface at x'



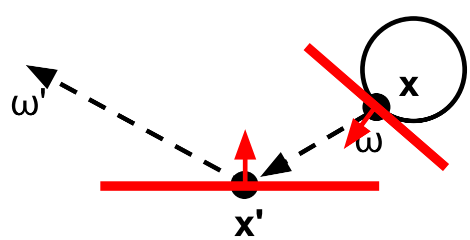
The Rendering Equation



$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\, dA$$

For each x, compute V(x,x'),
the visibility between x and x':
1 when the surfaces are unobstructed
along the direction ω, 0 otherwise

The Rendering Equation

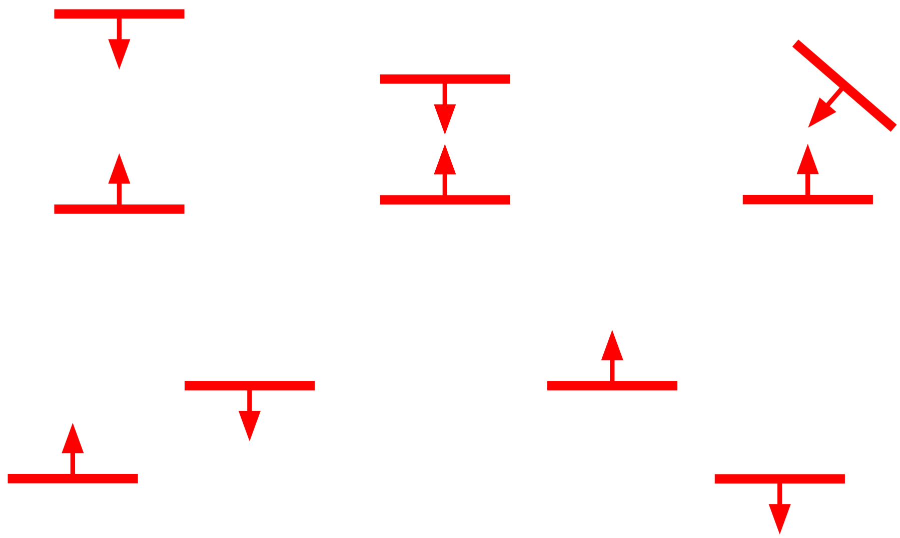


$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega')L(x,\omega)G(x,x')V(x,x')\, dA$$

For each x, compute G(x, x'), which
describes the on the geometric relationship
between the two surfaces at x and x’

Intuition about G(x,x')?

- Which arrangement of two surfaces will yield the greatest transfer of light energy? Why?



Rendering Equation → Radiosity

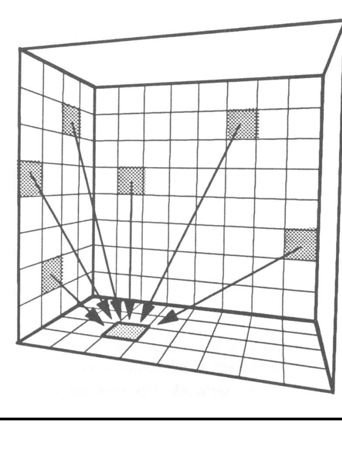
$$L(x',\omega') = E(x',\omega') + \int \rho_{x'}(\omega,\omega') L(x,\omega) G(x,x') V(x,x')\, dA$$

Radiosity assumption:
perfectly diffuse surfaces (not directional)

$$B_{x'} = E_{x'} + \rho_{x'} \int B_x \, G(x,x') V(x,x')$$

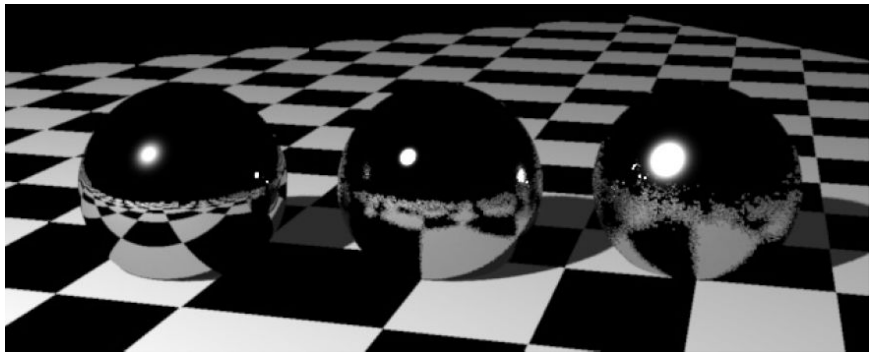
discretize

$$B_i = E_i + \rho_i \sum_{j=1}^{n} F_{ij} B_j$$

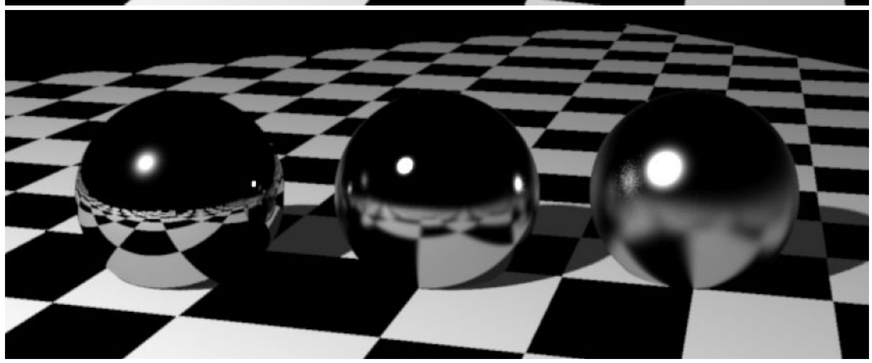


Questions?

1 glossy sample per pixel



256 glossy samples per pixel



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Pop Worksheet!

grey wall

Perform 5 iterations of progressive refinement radiosity

radiance @ iter 1	(10 , 10 , 10)			
undistributed @ iter 1	(0 , 0 , 0)			

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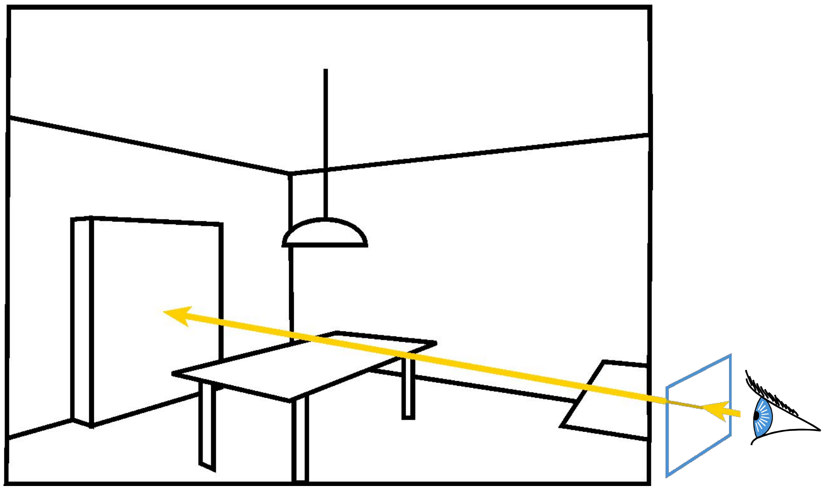
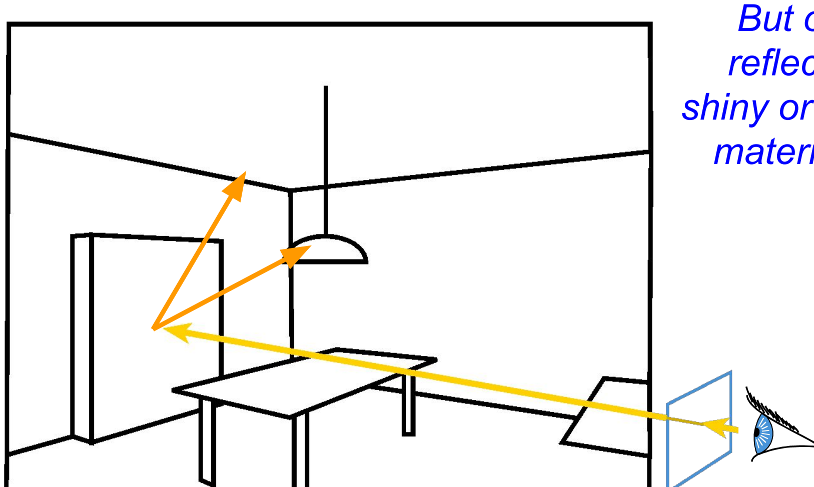
Ray Casting

- Cast a ray from the eye through each pixel



Ray Tracing

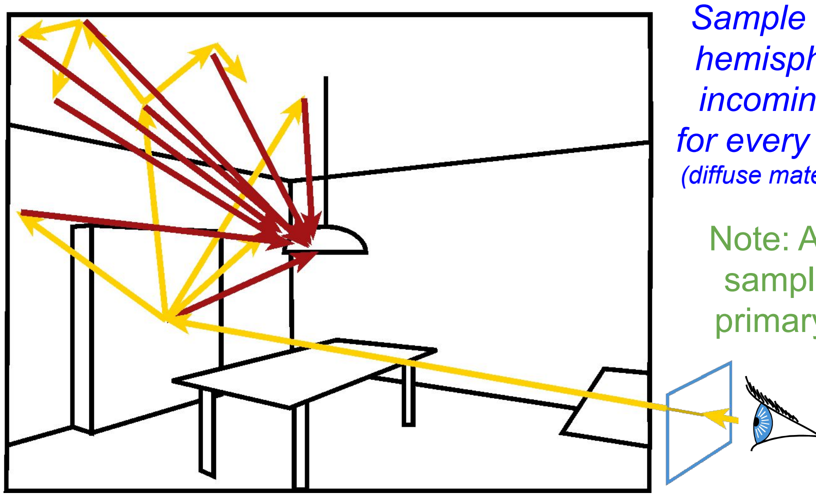
- Cast a ray from the eye through each pixel
- Trace secondary rays (light, reflection, refraction)



But only reflect off shiny or glossy materials...

Monte Carlo Ray Tracing

- Cast a ray from the eye through each pixel
- Cast random rays to accumulate radiance contribution
  - Recurse to solve the Rendering Equation

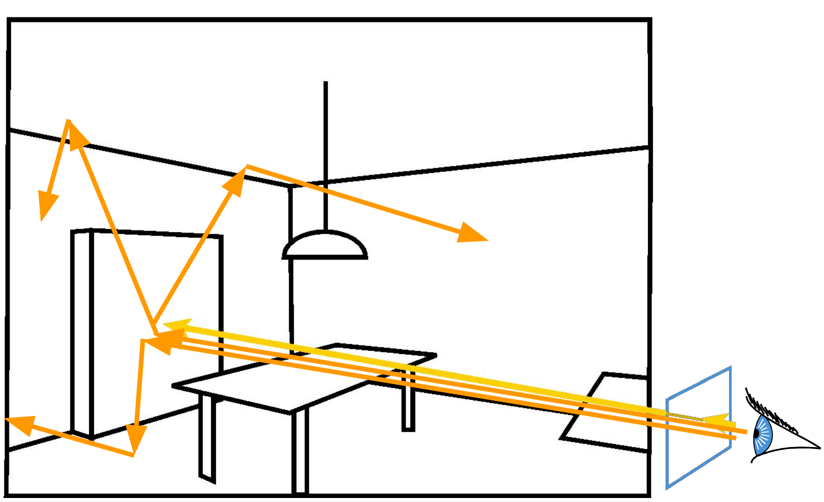


Sample the full hemisphere of incoming light for every surface
(diffuse materials too!)

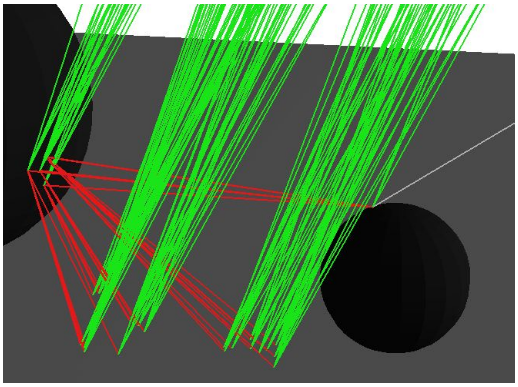
Note: Always sample the primary light

(Monte Carlo) Path Tracing

- Trace only one secondary ray per recursion
- But send many primary rays per pixel (performs antialiasing as well)



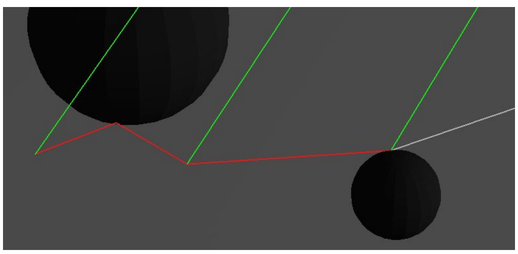
Ray Tracing vs. Path Tracing



2 bounces
5 glossy samples
5 shadow samples

How many rays cast per pixel?

1 main ray + 5 shadow rays +
5 glossy rays + 5x5 shadow rays +
5*5 glossy rays + 5x5x5 shadow rays
= 186 rays



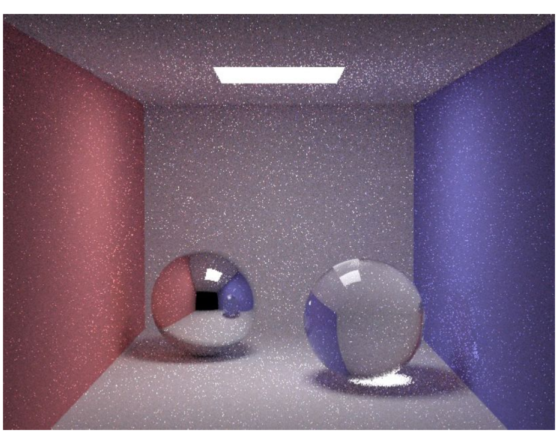
How many 3 bounce paths can we trace per pixel for the same cost?

186 rays / 8 ray casts per path
= ~23 paths

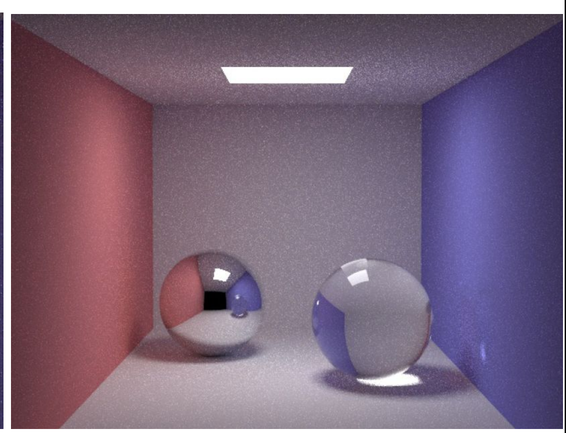
Which will probably have less error?

Questions?

10 paths/pixel



100 paths/pixel



Images from Henrik Wann Jensen

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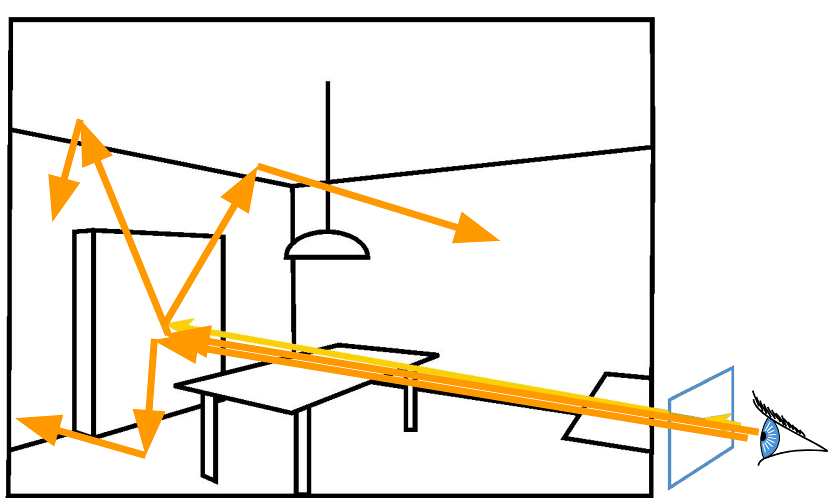
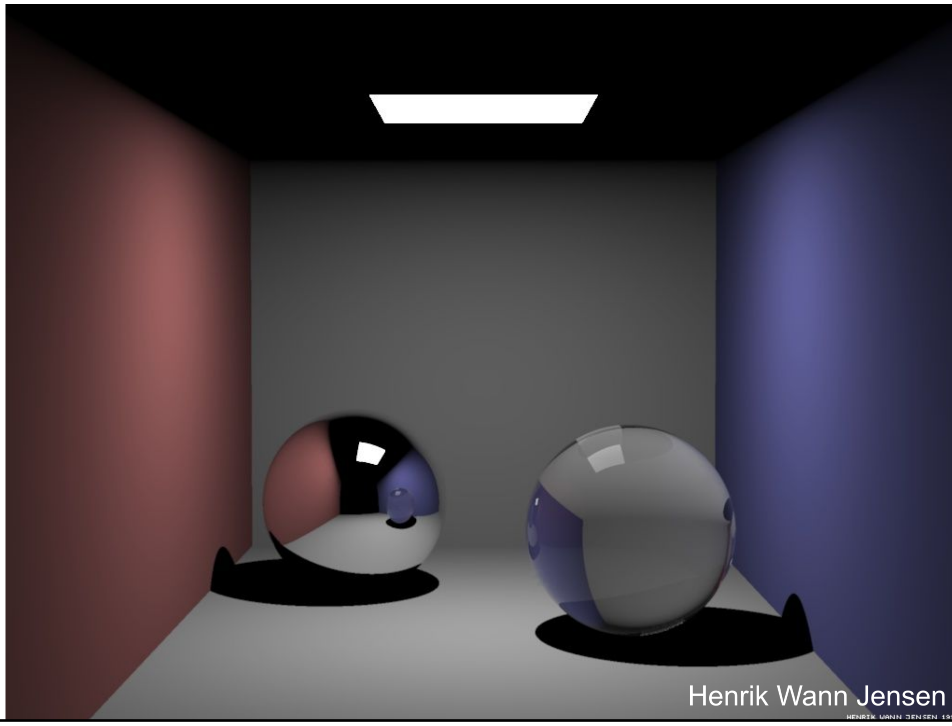
Path Tracing is costly

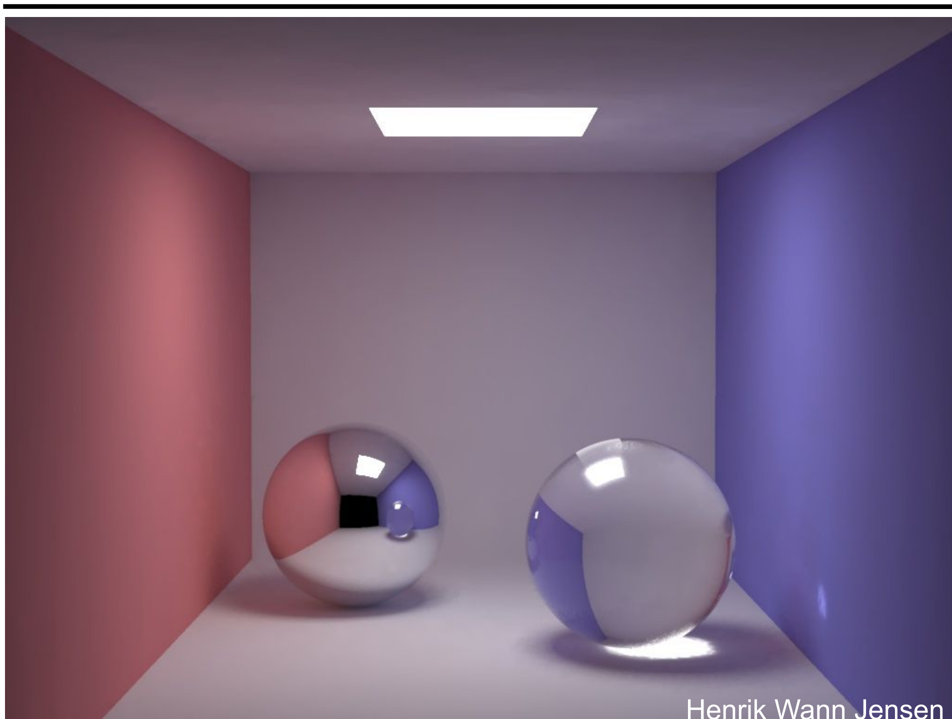
- Needs tons of rays per pixel



Direct Illumination



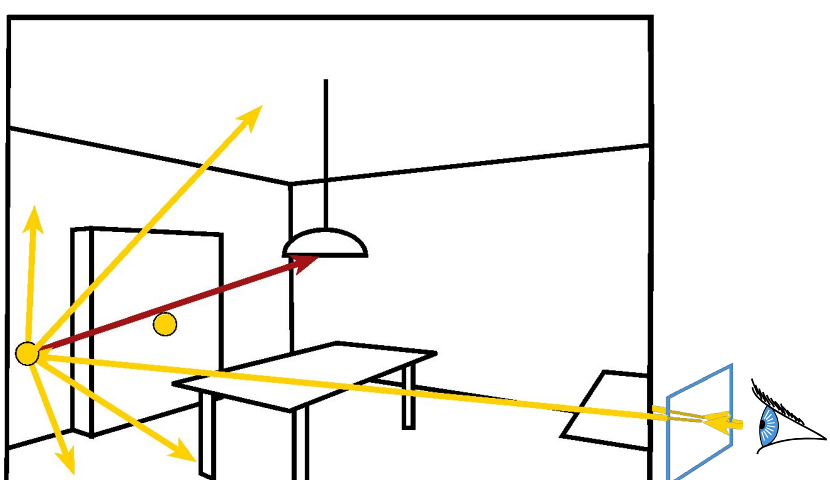
Global Illumination



Indirect Illumination: smooth

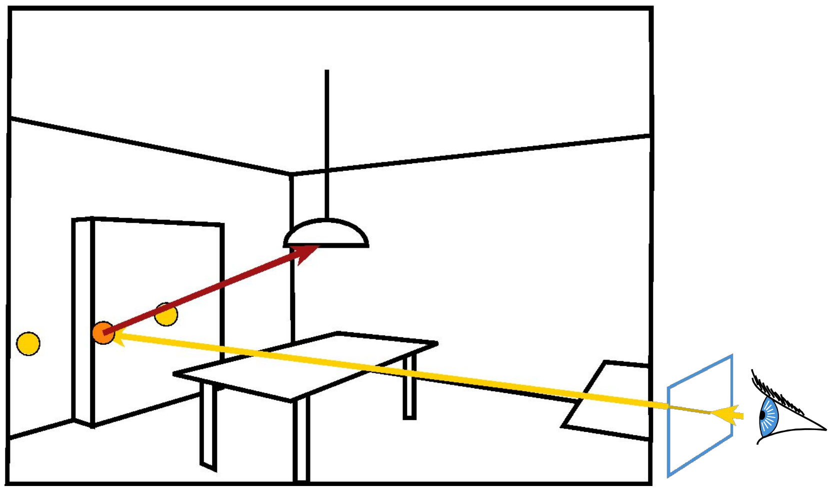
Irradiance Cache

- The indirect illumination is smooth
- Store the indirect illumination

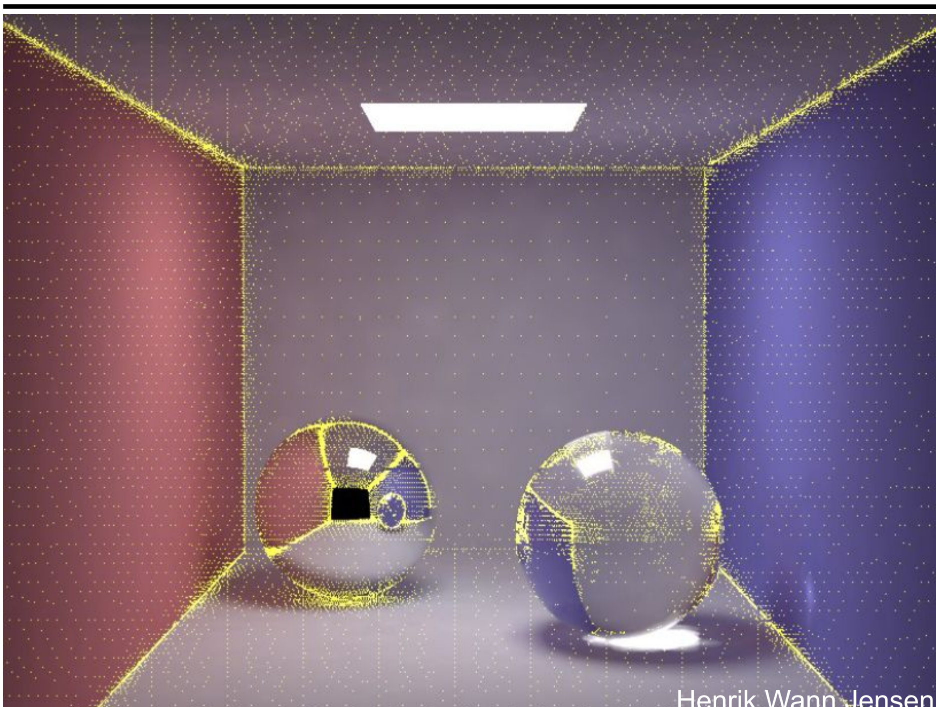


Irradiance Cache

- Interpolate nearby cached values
- But do full calculation for direct lighting

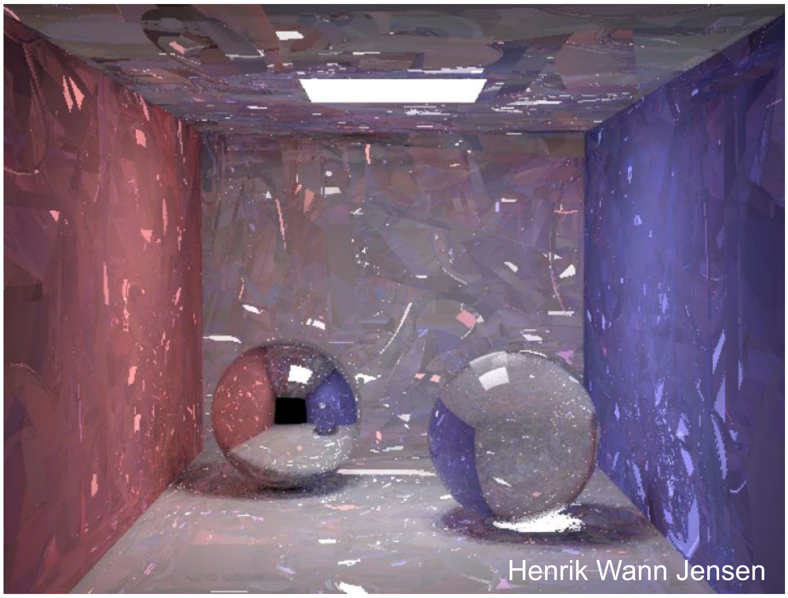


Irradiance Cache



Questions?

- Why do we need "good" random numbers?
  - With a fixed random sequence, we see the structure in the error



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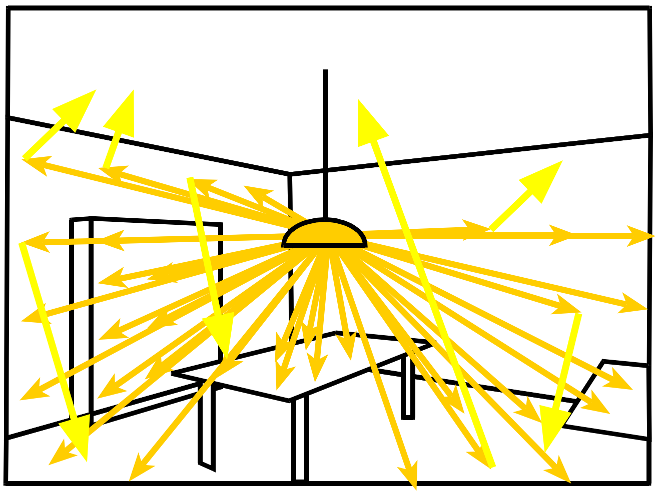
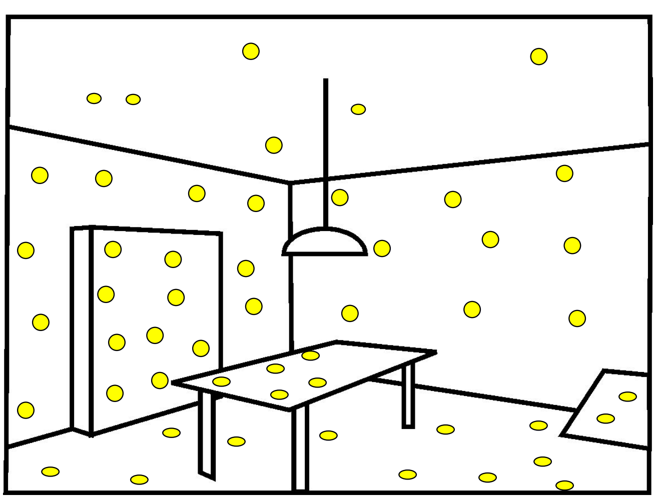
Photon Mapping

- Preprocess: cast rays from light sources
  - independent of viewpoint



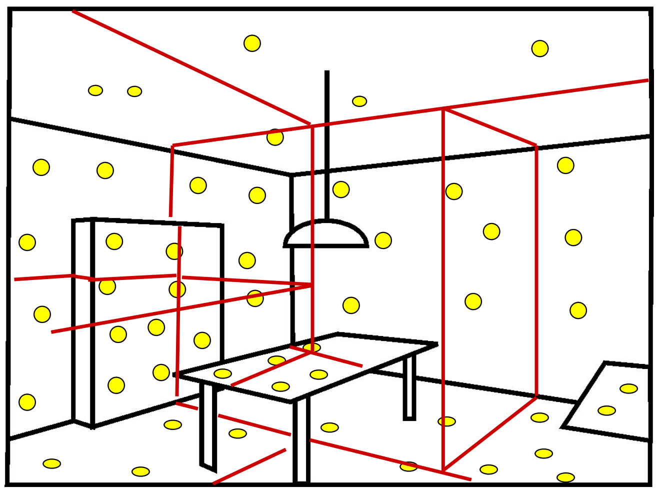
Photon Mapping

- Store photons
  - position + light power + incoming direction



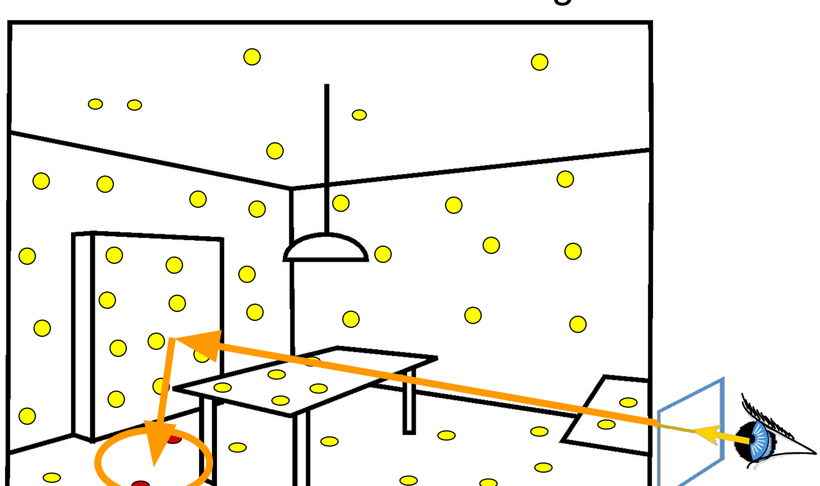
Storing the Photon Map

- Efficiently store photons for fast access
- Use hierarchical spatial structure (kd-tree)

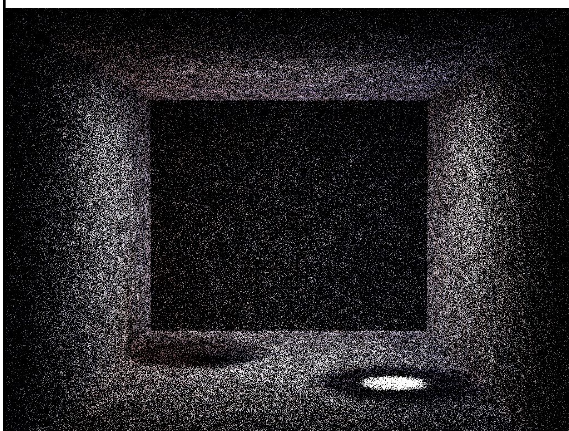
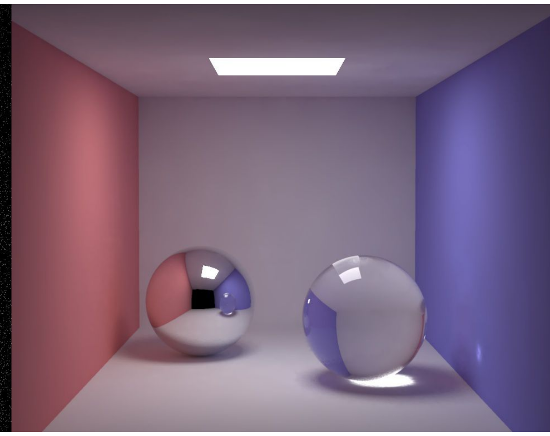


Rendering with Photon Map

- Cast primary rays
- For secondary rays: reconstruct irradiance using k closest photons
- Combine with irradiance caching and other techniques

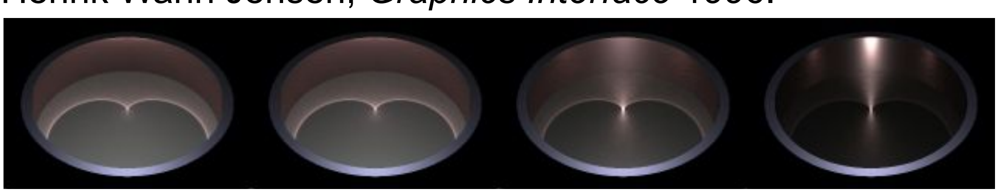


Photon Map Results

Readings for Today:

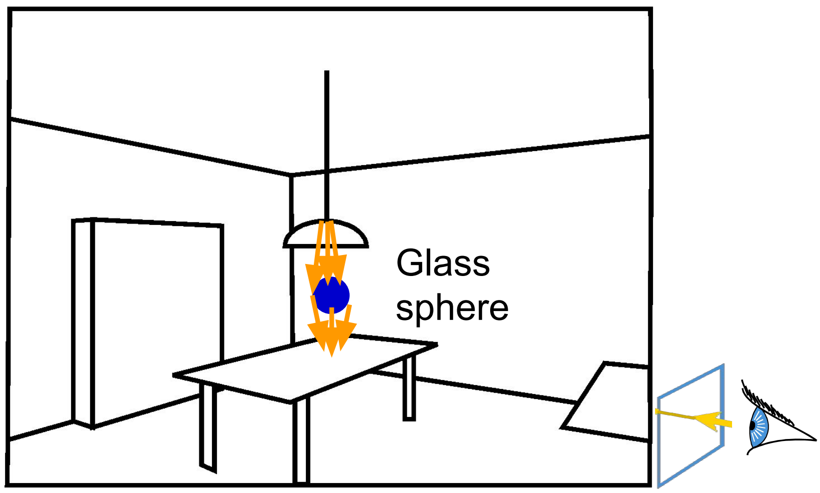
- "Rendering Caustics on Non-Lambertian Surfaces", Henrik Wann Jensen, *Graphics Interface* 1996.



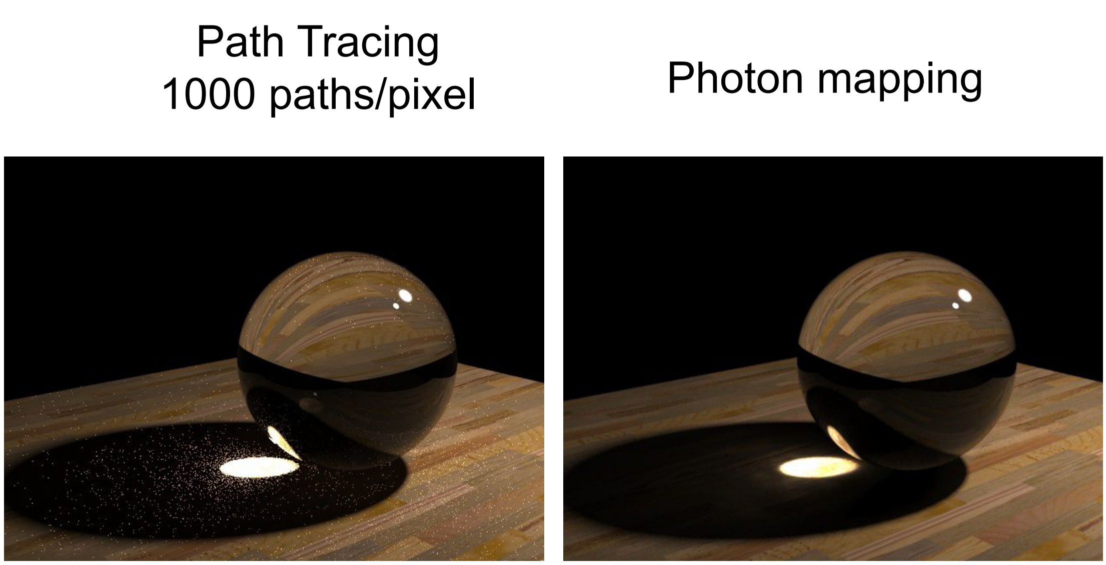
- "Global Illumination using Photon Maps", Henrik Wann Jensen, *Rendering Techniques* 1996.


Photon Mapping - Caustics

- Special photon map for specular reflection and refraction



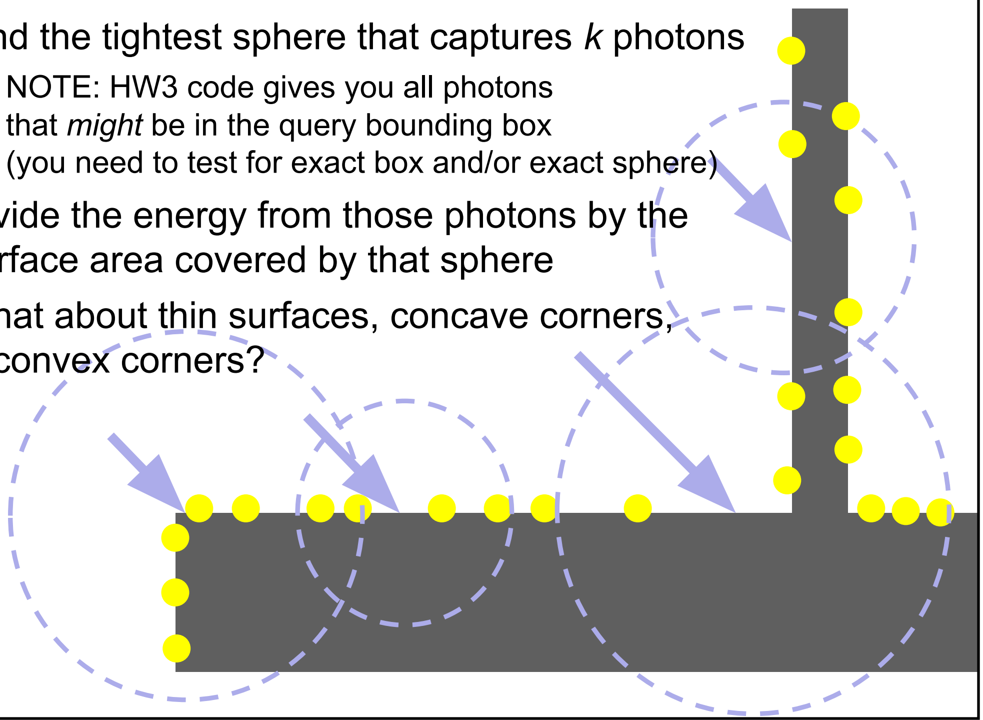
Comparison



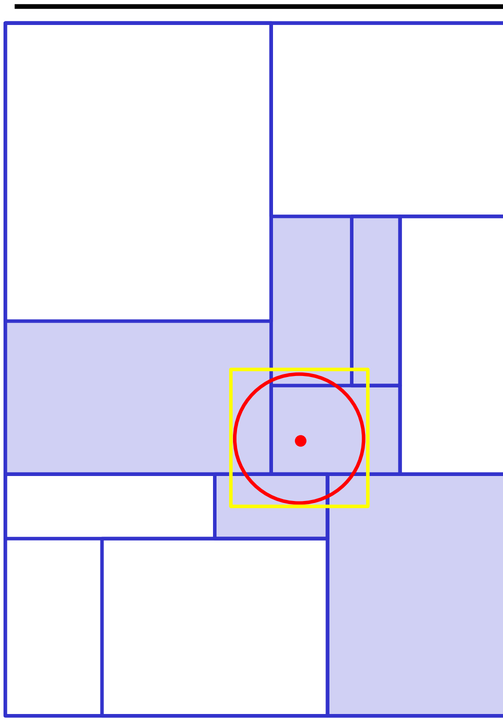
(similar rendering time)

Closest Photon Details

- Find the tightest sphere that captures *k* photons
  - NOTE: HW3 code gives you all photons that *might* be in the query bounding box (you need to test for exact box and/or exact sphere)
- Divide the energy from those photons by the surface area covered by that sphere
- What about thin surfaces, concave corners, & convex corners?



HW3: Photons in the k-d tree



- You start with query point & radius (red)
- You give the KDTree::CollectPhotonsInBox function a bounding box (yellow)
- The algorithm finds all k-d tree cells that overlap with bounding box (blue)
- The function returns all photons in those cells
- *You need to discard all photons not in your original query radius*

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Ray Grammar

- Classify local interaction:

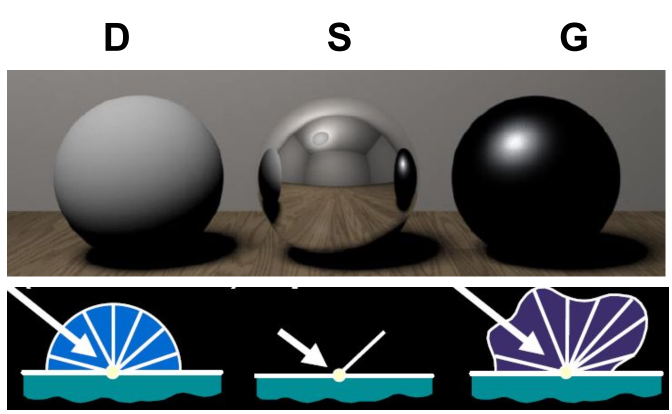
  E = eye

  L = light

  S = perfect specular reflection or refraction

  G = glossy scattering

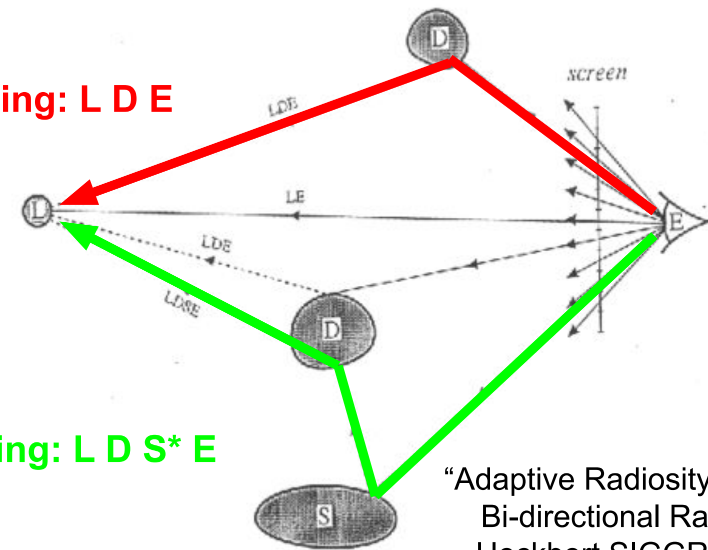
  D = diffuse scattering



From Dutre et al.'s slides

Classic Ray Casting/Tracing

Ray casting: L D E

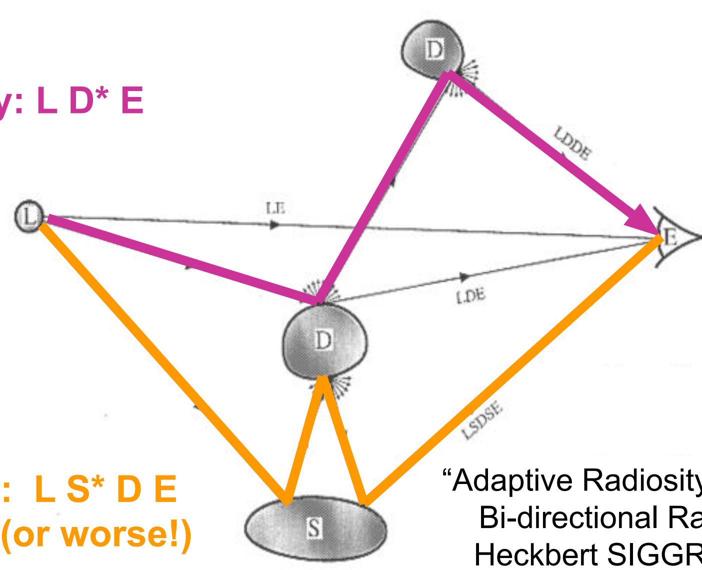


Ray tracing: L D S* E

"Adaptive Radiosity Textures for Bi-directional Ray Tracing"
Heckbert SIGGRAPH 1990

Photon Tracing

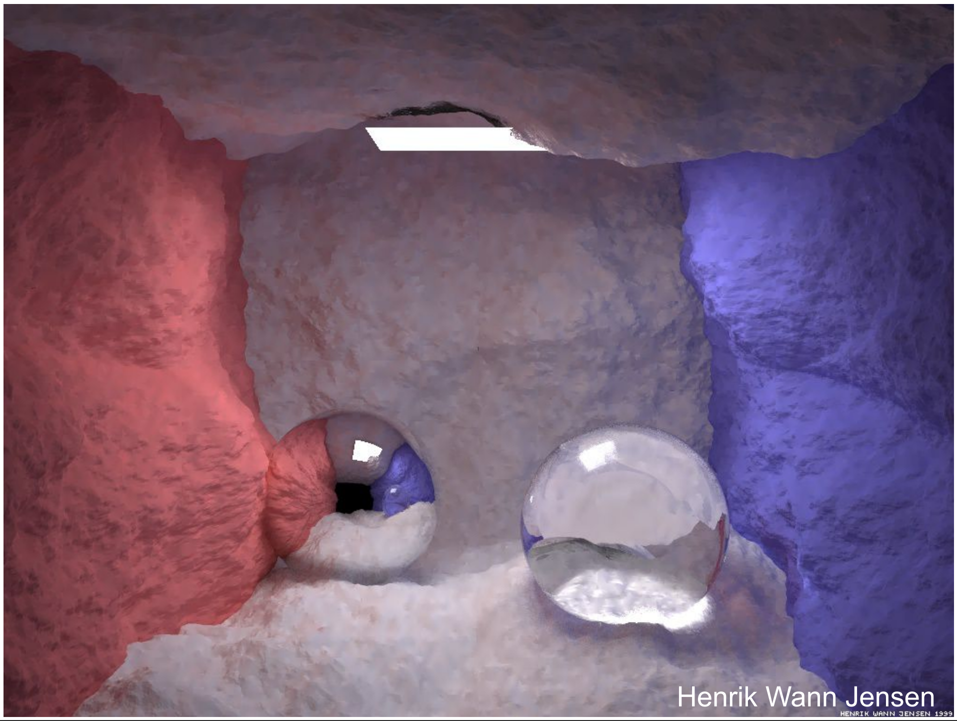
Radiosity: L D* E



Caustics: L S* D E
(or worse!)

"Adaptive Radiosity Textures for Bi-directional Ray Tracing"
Heckbert SIGGRAPH 1990

Questions?



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Readings for Next Time: *(pick one)*

"Correlated Multi-Jittered Sampling",
Andrew Kensler, Pixar Technical Memo, 2013

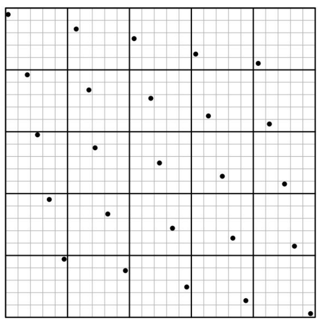

Figure 1: The canonical arrangement. Heavy lines show the boundaries of the 2D jitter cells. Light lines show the horizontal and vertical substrata of N-rooks sampling. Samples are jittered within the subcells.

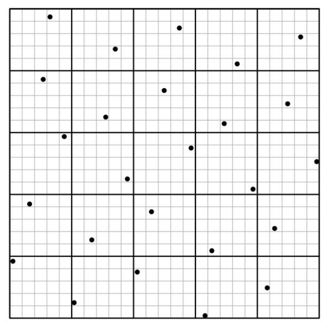

Figure 3: With correlated shuffling.

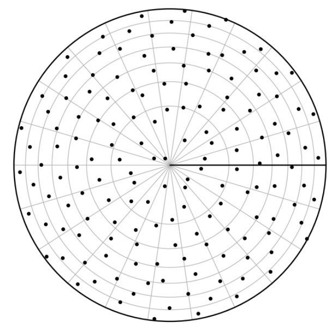

Figure 9: Polar warp with $m = 22, n = 7$.

[9]G. J. Ward and P. S. Heckbert. Irradiance gradients. In *Third Eurographics Rendering Workshop*, pages 85–98, May 1992.

Readings for Next Time: *(pick one)*

"Implicit Visibility and Antiradiance for Interactive Global Illumination"

Dachsbacher, Stamminger, Drettakis, and Durand
Siggraph 2007